AD-777 842

GAMMA RADIATION FROM FISSION PRODUCTS

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March 1974

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER GNE/PH/74-3	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD 777842
4. TITLE (and Subtitle) GAMMA RADIATION FROM FISSION PRODUCTS		5. TYPE OF REPORT & PERIOD COVERED MS Thesis 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ronald B. Drinkwater Captain, USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Institute of Technology Wright-Patterson Air Force Base, Ohio		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Weapons Laboratory Kirtland Air Force Base, N. M. 87117		12. REPORT DATE March 1974 13. NUMBER OF PAGES 56
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Approved for public release; IAW AFR 190-17

Jerry C. Hix, Captain, USAF
Director of Information

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fission-Product Gamma Radiation
Gamma Radiation

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An analytical study was made to determine the gamma radiation produced by the products of a fission device. The radiation during times from .10 sec to 2 min after fission was of special interest. Fission yield data were gathered for 5 fuels (fission spectra U^{235}, U^{238}, and Pu^{239}; and 14 MeV spectra U^{235} and U^{238}). Decay data were gathered for the fission products of these fuels. A computer program was written to process the data. Results could be obtained for a device of specified yield and fuel composition. The program results were not valid at times shorter than 1000

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sec after fission because gamma decay information was not available for many short lived products. However an approximation based on the long time program results is presented for use in obtaining short time total gamma energy rates.

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THESIS

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GAMMA RADIATION FROM FISSION PRODUCTS

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

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March 1974

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Preface

This study was made to determine quantitative gamma radiation rates from the products of a specified fission device. The .1 sec to 2 min time after fission period was of special interest. This period is of the most interest in weapon fireball radiation calculations.

I would like to thank Dr. Charles J. Bridgman for his guidance and interest in this study and Mrs. Audrey L. Crosby of the Vallecitos Nuclear Center for her assistance in obtaining needed data references.

Ronald B. Drinkwater

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Abstract

An analytical study was made to determine the gamma radiation produced by the products of a fission device. The radiation during times from .10 sec to 2 min after fission was of special interest. Fission yield data were gathered for 5 fuels (fission spectra U^{235}, U^{238}, and Pu^{239}; and 14 MeV spectra U^{235} and U^{238}). Decay data were gathered for the fission products of these fuels. A computer program was written to process the data which produced quantitative energy and number rates of interest in fission product gamma radiation analysis. Results could be obtained for a device of specified yield and fuel composition. The program results were not valid at times shorter than 1000 sec after fission because gamma decay information was not available for many short lived products. However an approximation based on the long time results is presented for use in obtaining short time total gamma energy rates.

GAMMA RADIATION FROM FISSION PRODUCTS

I. Introduction

Purpose

This study was made to determine the gamma radiation given off by the fission products of a specified device as a function of time after the fission process occurred. The study was primarily designed to produce results for use in the study of delayed nuclear weapon effects. The results could be used in reactor product radiation studies, especially for severe excursion analysis.

Aircraft flying in the vicinity of a nuclear weapon detonation may not be harmed by prompt weapon effects, however their flight paths may pass through the radioactive weapon products. The gamma radiation from these products may cause damage to the aircraft and its crew. Elementary buoyant body calculations indicate a weapon fireball would rise to the tropopause (above typical aircraft altitudes) in approximately 2 min. If the aircraft were to enter the fireball in less than 0.1 sec after weapon detonation, prompt weapon effects would most surely have destroyed it. Thus, the time period of 0.1 sec to 2 min after fission was of special interest.

Terms Defined

Two terms used frequently in this report must be clearly defined; "Fission Fragment" and "Fission Product".

For the purposes of this report, a fission fragment is an atom that is formed directly by the fission process. A fission product is an atom that is either formed by the fission process or present as the result of fission fragment decays.

Overview

Fission yield data and decay data on fission products were gathered and compiled for computer processing. A computer program was written to process the data. The program output included both energy and number rates (see Table I). The 17 gamma energy rates (rates 2-18) are the same as 17 of the 18 gamma groups used in an AFIT prompt effects code (SV Code). Group I (8.00-10.00 MeV) was not included because no gammas of this energy were encountered in this study.

Table I	
Program Output Rates	
Race Index	Definition
1	Total Activity (Decays/sec)
2	6.50-8.00 MeV Gamma Rate (MeV/sec)
3	5.00-6.50 MeV Gamma Rate (MeV/sec)
4	4.00-5.00 MeV Gamma Rate (MeV/sec)
5	3.00-4.00 MeV Gamma Rate (MeV/sec)
6	2.50-3.00 MeV Gamma Rate (MeV/sec)
7	2.00-2.50 MeV Gamma Rate (MeV/sec)
8	1.66-2.00 MeV Gamma Rate (MeV/sec)
9	1.33-1.66 MeV Gamma Rate (MeV/sec)
10	1.00-1.33 MeV Gamma Rate (MeV/sec)
11	.80-1.00 MeV Gamma Rate (MeV/sec)
12	.60- .80 MeV Gamma Rate (MeV/sec)
13	.40- .60 MeV Gamma Rate (MeV/sec)
14	.20- .40 MeV Gamma Rate (MeV/sec)
15	.20- .30 MeV Gamma Rate (MeV/sec)
16	.10- .20 MeV Gamma Rate (MeV/sec)
17	.05- .10 MeV Gamma Rate (MeV/sec)
18	.02- .05 MeV Gamma Rate (MeV/sec)
19	Total Gamma Number Rate (Gammas/sec)
20	Total Gamma Energy Rate (MeV/sec)

This report deals mainly with the analysis of the fission of U^{235} (fission spectra fission). The other 4 fuels covered by the study were analyzed and the results were generally the same as those for U^{235} (see Table II).

Table II Fuels Covered by This Study
U^{235} (Fission Spectra)
U^{238} (Fission Spectra)
Pu^{239} (Fission Spectra)
U^{235} (14 MeV)
U^{238} (14 MeV)

Assumptions and Limitations

A large amount of fission yield and decay data was needed for this study. To cover all the possible fission products, one would have to include data on approximately 107 mass chains. This would involve roughly 400 fission fragments and 500-600 radioactive fission products. Collection and compilation of data on all possible fission products would have taken more time than was allotted for this study. The data used was limited to those fission products of U^{235} (fission spectra fission) which are members of mass chains with a fission yield of 1%, or higher. This amounted to mass chains, which involve 123 fission fragments and 178 radioactive fission products. Specifically, data for fission products in mass chains 84 through 105 and 129 through

149 were collected and used in the program. As a result, the program accounted for the following percentages of fission products from the respective fuels (see Table III).

Table III

Fission Products Accounted For

Fuel	Program Product Yield
U^{235} (Fission Spectra)	98.8%
U^{238} (Fission Spectra)	95.5%
Pu^{239} (Fission Spectra)	88.7%
U^{235} (14 MeV)	82.9%
U^{238} (14 MeV)	83.4%

The program will compute results for any specified amount and mixture of these fuels. A fraction of fission products accounted for from the specified device is computed. The rate results are adjusted by multiplication by the inverse of this fraction so they will reflect an "adjusted" 100% fission product coverage. This assumes the gamma radiation from the missing products is the same as that from the included products.

The most serious limitation in this study is a result of the fact that gamma radiation data was not available for many of the short lived products. Of the 178 products considered, gamma radiation data was not available for 84 products. Of these 84 products, 19 had half lives over 1 minute, 6 had half lives over 10 minutes, and 2 had half

lives over 1 hour. Using the fact that relatively all activity dies out after 10 half lives as a basis, it is considered that 1000 sec after fission is a conservative minimum for valid program energy rate results. Thus, program energy rate results are not valid for the time period of most interest, .1 sec to 2 min after fission, however, an approximation developed in Chapter IV allows total gamma energy rate calculations for this time region.

Relative gamma intensities were available for 16 of the 84 radioactive products with unknown absolute gamma intensities.

Table IV lists gamma radiation data for 2 fission products to illustrate what is meant by absolute and relative gamma intensities (Ref 8:224).

Table IV

Kr^{89}		Rb^{90}	
Gamma (MeV)	Relative Intensity	Gamma (MeV)	Absolute Intensity
0.23	85.0	0.53	4%
0.36	28.0	0.72	4%
0.51	42.0	0.83	56%
0.60	100.0	0.86	6%
others	< 100.0	others	< 56%

For the decay of Kr^{89}, only relative gamma intensities are known, i.e. the 0.60 MeV gamma is the most frequent gamma, and for every 100 0.60 MeV gammas there would be 42 0.51 MeV gammas. The number of any gamma produced per decay of

Kr^{89} is unknown. For the decay of Rb^{90}, absolute gamma intensities are known, for 100 Rb^{90} decays, 56 0.83 MeV gammas would be produced. It was observed that the absolute intensities of the most frequent gammas from all the products considered generally varied from 100% to 1.0%, with a few exceptions lower than 1.0%. Based on this range of absolute intensity values, the absolute intensities of the most frequent gammas, from the 16 products for which only relative intensities were known, were set at 1.0%. With the absolute intensity of the most frequent gamma known, absolute intensities of the remaining gammas are easily calculated. The absolute intensity of 1.0% was considered to be generally low, and was chosen so that the chances that estimated gamma radiation would not dominate over known gamma radiation in the results would be minimized. The gamma decay data for the remaining products with unkrown absolute gamma decay data were set at zero. This dictates that the short time (less than 1000 sec after fission) energy rates and gamma number rates will be low.

The program activity results (Rate 1, see Table I) do not have the limitation previously described. The half lives of all products used in the program were known. However, most mass chains have some members for which half lives are unknown. This study used the first member of the mass chain with a known half life as the first member of that chain. Table V shows an example of the mass chain information used to compile data for the program (Ref 9:24).

Table V

Typical Mass Chain

Nuclide	Half Life	Cumulative Fission Yield (for Fission Spectra U^{235})
34 Se^{96}	Unknown	Not Listed
35 Br^{96}	Unknown	7.56×10^{-9}%
36 Kr^{96}	Unknown	9.08×10^{-5}%
37 Rb^{96}	.23 sec	.0519%
38 Sr^{96}	4.0 sec	1.69%
39 Y^{96}	2.3 min	5.48%
40 Zr^{96}	Stable	6.22%

Thus, 37 Rb^{96} was used as the first member of the chain with a fission yield of .0519% for fission spectra U^{235}. The second member was 38 Sr^{96}, with an individual yield of 1.64% (1.69% - .0519%), etc. The first members of the mass chains with known half lives generally had half lives of .1 sec to 1 min. It is probable that the members with unknown half lives have very short half lives (less than 1 sec) since they are farther from stability than the members with known half lives. Thus some activity before 1 sec after fission is not accounted for and therefore program activity results are considered low for times less than 1 sec after fission.

Data References

The references used to gather fission yield and decay data are critical to the validity of this study. They are

listed here in the text to give the reader an idea of the scope of the basic data used in this study.

Fission yield data was gathered exclusively from the 1972 General Electric Company report, "Compilation of Fission Product Yields" by Meek and Rider (Ref 7). This report presents a consolidated, current listing of this data.

Half life and decay branching data was gathered mainly from the same report, with occasional reference to other sources for confirmation purposes.

Gamma radiation data was gathered from four sources; "Handbook of Chemistry and Physics" (Ref 10), "Table of Isotopes" (Ref 8), "Gamma-Ray Energies and Intensities" (Ref 6), and applicable editions of the periodical, Nuclear Data.

II. Calculation Method

The basic inputs used in this study are device yield, device composition and time after fission. The outputs are various energy and number rates as described in Table I.

First, the number of atoms of each fission fragment produced by the device is calculated. The device yield and device composition figures are used to compute the number of fissions of each type fuel that occurred. The number of fissions of each fuel is then multiplied by appropriate fission yield data to compute the number of atoms of each fission fragment produced by that fuel. The total number of atoms of each fission fragment produced by the device is then calculated by adding up the amounts of that fission fragment produced by the component fuels.

Next, the initial number of atoms of particular fission fragment and the specified time after fission are used to calculate the components of the various rates described in Table I caused by the decay of this particular fission fragment and its daughters. A two step procedure is used to compute the various rates for each fission fragment decay chain. Running totals of these rates are kept and will reflect output rates for the entire device after the procedure has been applied to all fission fragments.

The first step in the procedure computes the number of atoms of the fission fragment and its daughters present at the specified time after fission. Although the various isotopes here may be the same as those present in the

decay chains of other fission fragments, this step only accounts for those particular atoms present as a direct result of the initial quantity of the particular fission fragment being processed. Thus after the initial quantities of all fission fragments have been processed, rates reflecting the effects of the entire device will have been calculated. The basic radioactive transformation equations, "Bateman Equations" (Ref 7:243) were used in this step.

Given a simple decay chain for fission fragment A_1:

$$A_1 \rightarrow A_2 \rightarrow A_3 \rightarrow A_4 \rightarrow A_5 \rightarrow \text{etc.}$$

$$A_1(t) = A_1(0)\, e^{-\lambda_1 t} \tag{1}$$

$$A_2(t) = A_1(0)\left(\frac{\lambda_1}{\lambda_2-\lambda_1} e^{-\lambda_1 t} + \frac{\lambda_1}{\lambda_1-\lambda_2} e^{-\lambda_2 t}\right) \tag{2}$$

Or Generally:

$$A_n(t) = C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t} + \ldots . \tag{3}$$

Where: $$C_1 = \frac{\lambda_1\lambda_2\ldots\lambda_{n-1}}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)\ldots(\lambda_n-\lambda_1)} A_1(0) \tag{4}$$

$$C_2 = \frac{\lambda_1\lambda_2\ldots\lambda_{n-1}}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)\ldots(\lambda_n-\lambda_2)} A_1(0) \tag{5}$$

$$\vdots$$

$$C_n = \frac{\lambda_1\lambda_2\ldots\lambda_{n-1}}{(\lambda_1-\lambda_n)(\lambda_2-\lambda_n)\ldots(\lambda_{n-1}-\lambda_n)} A_1(0) \tag{6}$$

Where: t is the specified time after fission.

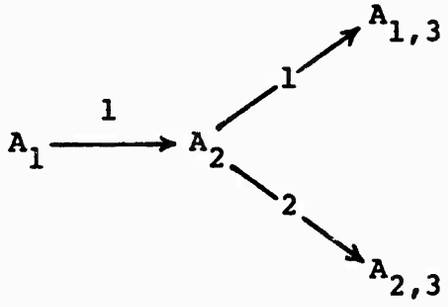
$A_1(0)$ is the initial number of atoms of fission fragment A_1.

$A_n(t)$ is the number of atoms of the nth member of the chain present at time t.

λ_n is the decay constant of the nth member of the chain.

These equations are easily adapted to computer processing with proper indexing of the particular variables.

Decay chain branching occurs in many of the fission fragment decay chains. For the simple branching decay chains:



the decay is split into indexed chains as indicated. The branching fractions are readily available in the references; i.e. the fraction of A_2 that decays to $A_{1,3}$ (BF_1) and the fraction of A_2 that decays to $A_{2,3}$ (BF_2).

The following equations account for all atoms present at time t for the simple branching decay chain shown above.

$$A_1(t) = A_1(0)\, e^{-\lambda_1 t} \tag{7}$$

$$A_2(t) = A_1(0)\left(\frac{\lambda_1}{\lambda_2-\lambda_1} e^{-\lambda_1 t} + \frac{\lambda_1}{(\lambda_1-\lambda_2)} e^{-\lambda_2 t}\right) \tag{8}$$

$$A_{1,3}(t) = A_1(0)BF_1\left(\frac{\lambda_1\lambda_2}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)} e^{-\lambda_1 t} + \frac{\lambda_1\lambda_2}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)} e^{-\lambda_2 t} + \frac{\lambda_1\lambda_2}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)} e^{-\lambda_3 t}\right) \tag{9}$$

$$A_{2,3}(t) = A_1(0)BF_2 \left(\frac{\lambda_1\lambda_2}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)} e^{-\lambda_1 t} + \frac{\lambda_1\lambda_2}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)} e^{-\lambda_2 t} + \frac{\lambda_1\lambda_2}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)} e^{-\lambda_3 t} \right) \quad (10)$$

These equations are, again, easily adapted to computer routines with proper indexing of the particular variables, even in quite complicated branching situations.

The second step in the procedure multiplies the number of atoms of each radioactive isotope by its respective decay constant to yield activity (decay/sec) of that isotope in the chain. This activity is then multiplied by decay factors for the particular isotope to give the rates contributed by this isotope, eg activity times total gamma energy per decay of this isotope would yield total gamma energy per second contributed by the number of atoms of this particular isotope present in the chain being processed. The rates from all isotopes in the chain are then summed to reflect the rates produced by the entire chain.

Appendix A gives a listing of the Computer Program used to perform the calculations.

III. Program Results

The results produced by the program consist of various energy and number rates as described in Table I. These rates are quantitative and represent the output from the products of a device of specified yield and composition. The results presented in this chapter are scaled to units of rate per fission of U^{235} (fission spectra fission). These units compare more readily to other studies and eliminate the need to specify the device yield. As previously mentioned in Chapter I, the results for the other fuels are generally the same as those computed for U^{235}.

Total Gamma Energy Rate

Figure 1 shows the total gamma energy rate as a function of time after fission as calculated by the computer program. The energy rate values are considered low for time of less than 1000 sec because of the unknown gamma decay factors on many short-lived products which were arbitrarily set at zero in the program data.

Spectrum

The computer code produces 17 gamma-energy-group energy rates as shown in Table I. These results are subject to the same limitations as the total gamma energy rate. In Figure 2, the group energy rates are consolidated into 3 energy groups and normalized so that total energy rate equals one. Figure 2 indicates very erratic spectral behavior over the times covered, however a general "softening"

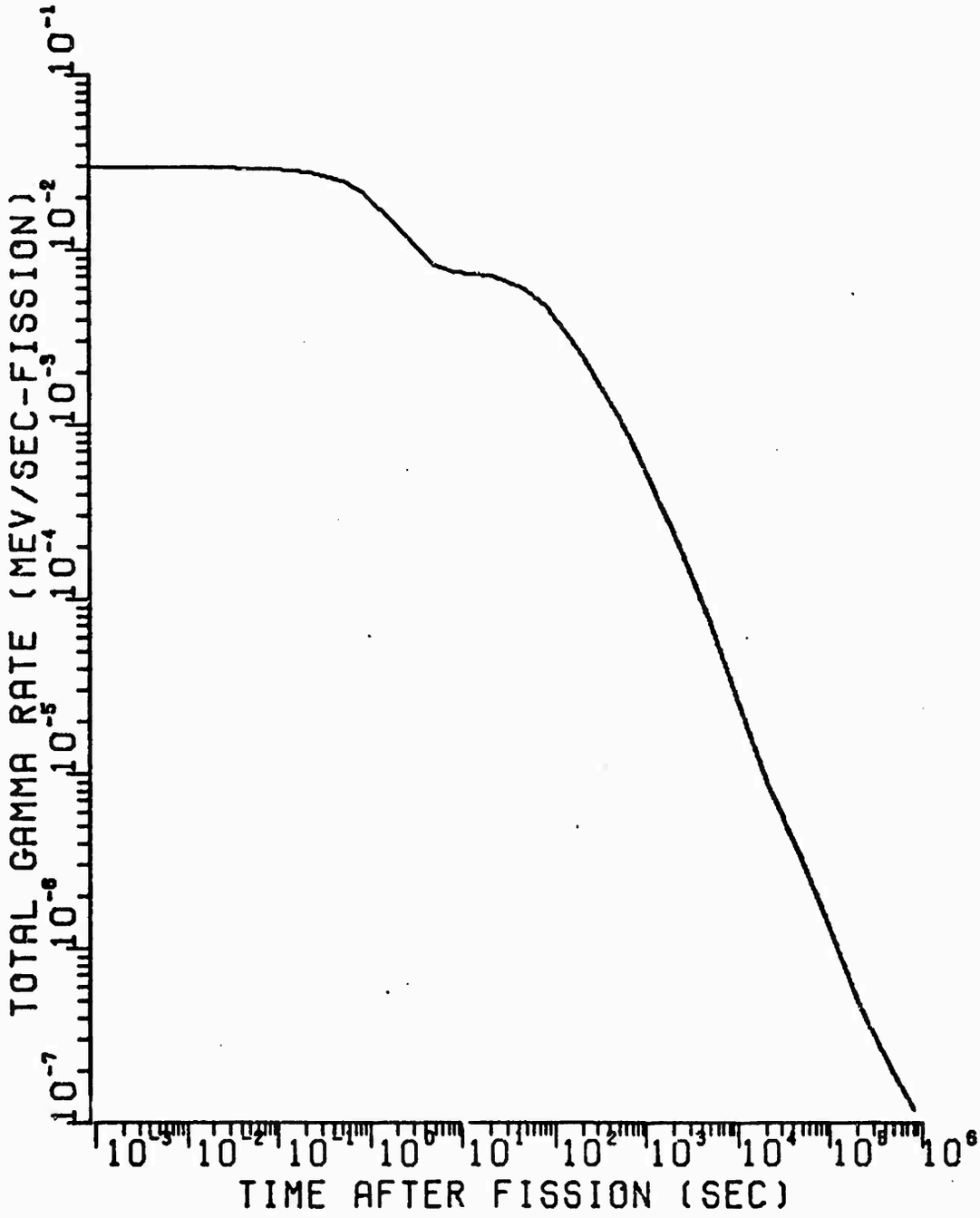


Figure 1. Total Gamma Energy Rate

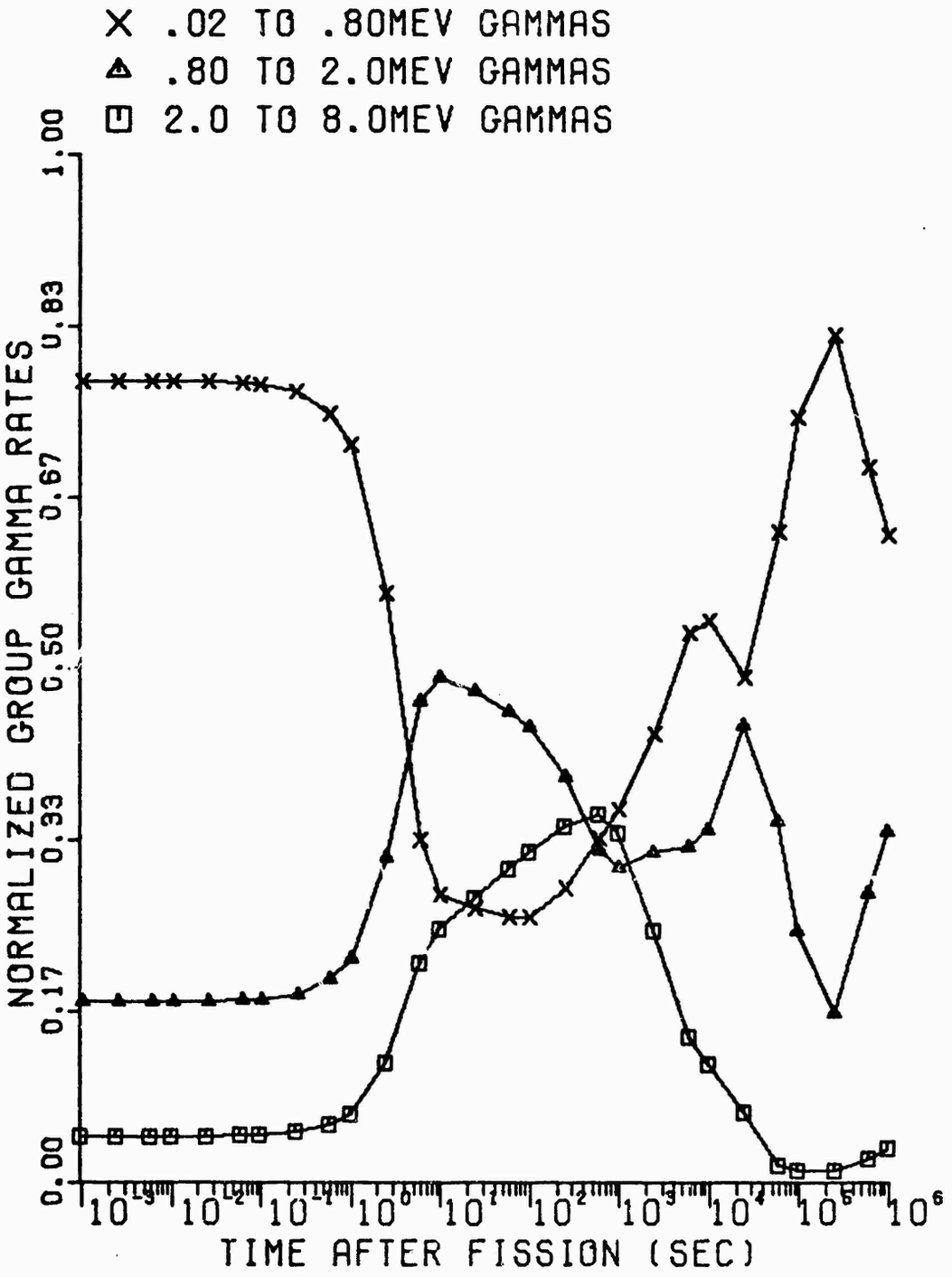


Figure 2. Normalized Gamma-Energy-Group Energy Rates

trend (the tendency for the total gamma energy to be composed of mostly lower energy gammas) is noted as times progress beyond 1000 sec.

Perhaps a better look at the gamma radiation spectrum is given by Table VI which lists average energy per gamma as a function of time after fission. The limitations below 1000 sec still apply.

Table VI

Average Gamma Energies

Time After Fission (sec)	Average Gamma Energy (MeV/gamma)
1×10^{-3}	.529
1×10^{-2}	.528
1×10^{-1}	.530
1×10^{0}	.553
1×10^{1}	.867
1×10^{2}	1.068
1×10^{3}	1.054
1×10^{4}	.873
8.64×10^{4} (1 day)	.674
6.05×10^{5} (1 week)	.626

Total Activity

Figure 3 shows the total product activity as a function of time after fission. These results are considered accurate for times greater than 1 sec after fission. The activity results for times below 1 sec are considered low because

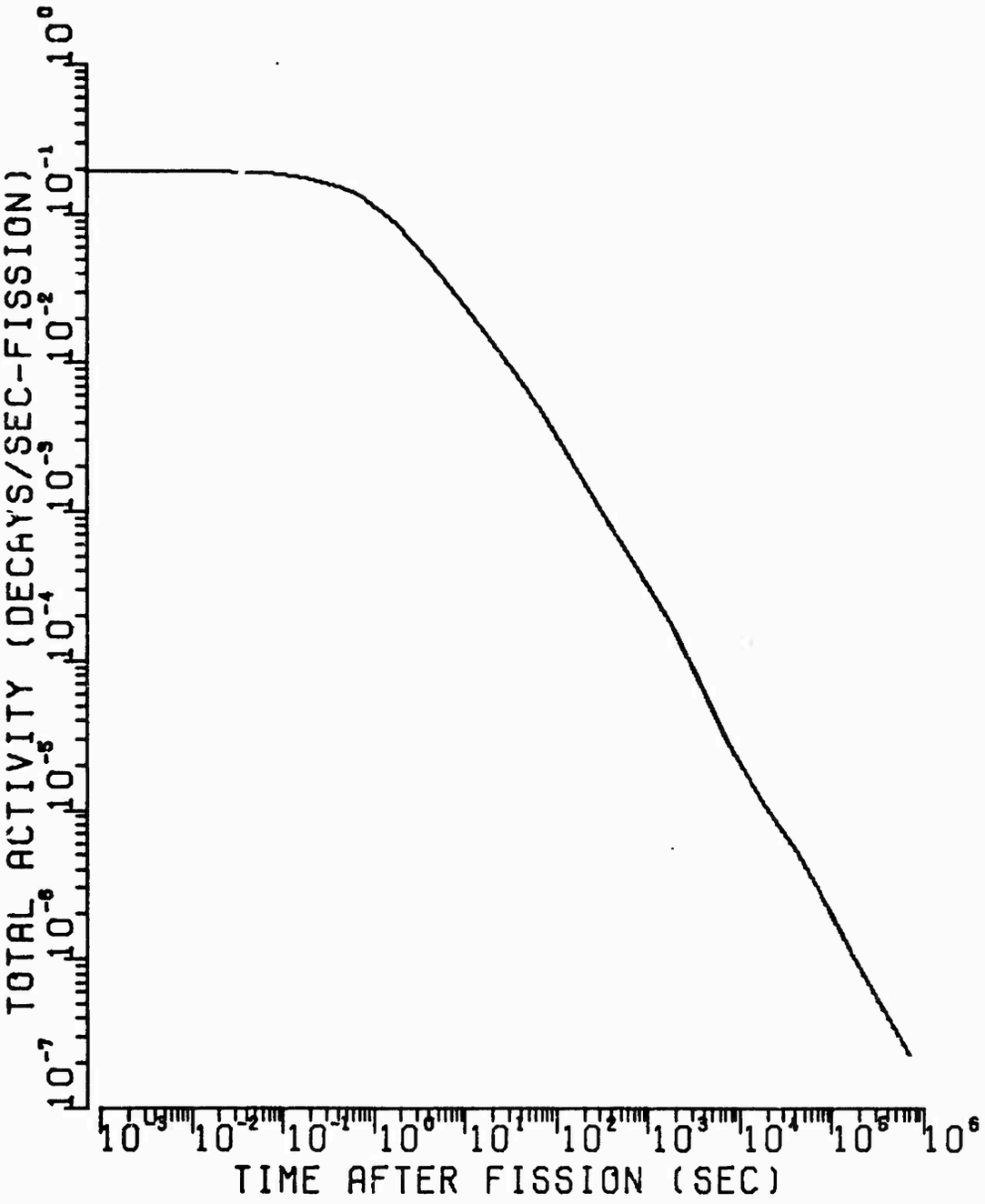


Figure 3. Total Activity

products with unknown half lives (very short lived products) were not included in the computer code.

IV. Early Time Approximations

Although the program results presented in Chapter III are considered good for late times, these results do not cover the time period of most interest; .1 sec to 2 min after fission. Two methods were used in an attempt to find a procedure that would produce good total gamma energy rate values for the .1 sec to 2 min time period; use of the familiar "$T^{-1.2}$ Law" and an independent approach developed by the author. As in Chapter III, the results presented in this chapter are in units of rate per fission of U^{235} (fission spectra fission).

"$T^{-1.2}$ Law" Approximation

The familiar "$T^{-1.2}$" type approximation is cited as a method of obtaining product radiation rate values for times less than 1000 hours after fission (Ref 4:421) or 6 months after fission (Ref 1:323). It is stated that this approximation is good only for times in excess of 10 sec after fission (Ref 11: 1027-1029). This method involves the use of the equation:

$$A(t) = A_o t^{-1.2} \tag{11}$$

where: A_o is the radiation rate at unit time after fission.

t is the time after fission of interest in units compatible with A_o.

A(t) is the approximated radiation rate at time t.

Thus, if the radiation rate at any time after fission is known, an approximation of the rate for any other time can

be made (within the specified time limits).

Using the program total gamma energy rate at 1000 sec after fission as A_o, this approximation was used to compute rate values for the other times after fission. Figure 4 shows the approximation results compared with the program results.

Both the approximation results and the program results were integrated by trapezoidal numerical methods to determine total product gamma energy released per fission. The time span covered by the integration was from 10^{-6} sec through 10^{12} sec after fission. The integration time period starts after nuclear weapon burn times (considered less than 10^{-7} sec). Negligible gamma energy per fission is contributed by times greater than 10^{5} sec in both cases. The results were 308 MeV/fission for the approximation and 5.03 MeV/fission for the program results. It appears the approximation allows far too much product gamma radiation when one compares the integration results to generally accepted values of around 6 MeV/Fission (Ref 4:13). Even if only the time span of interest, .1 sec through 2 min, is used as the integration period, the approximation results yield a product gamma energy of more than 40 MeV/fission. Clearly the "$T^{-1.2}$ Law" approximation produces total gamma energy rates that are too large over the .1 sec to 2 min time after fission region. This would be expected, since the use of the "$T^{-1.2}$ Law" at times below 10 sec is not considered valid (Ref 10: 1029) and because numerous experimental and theoretical total

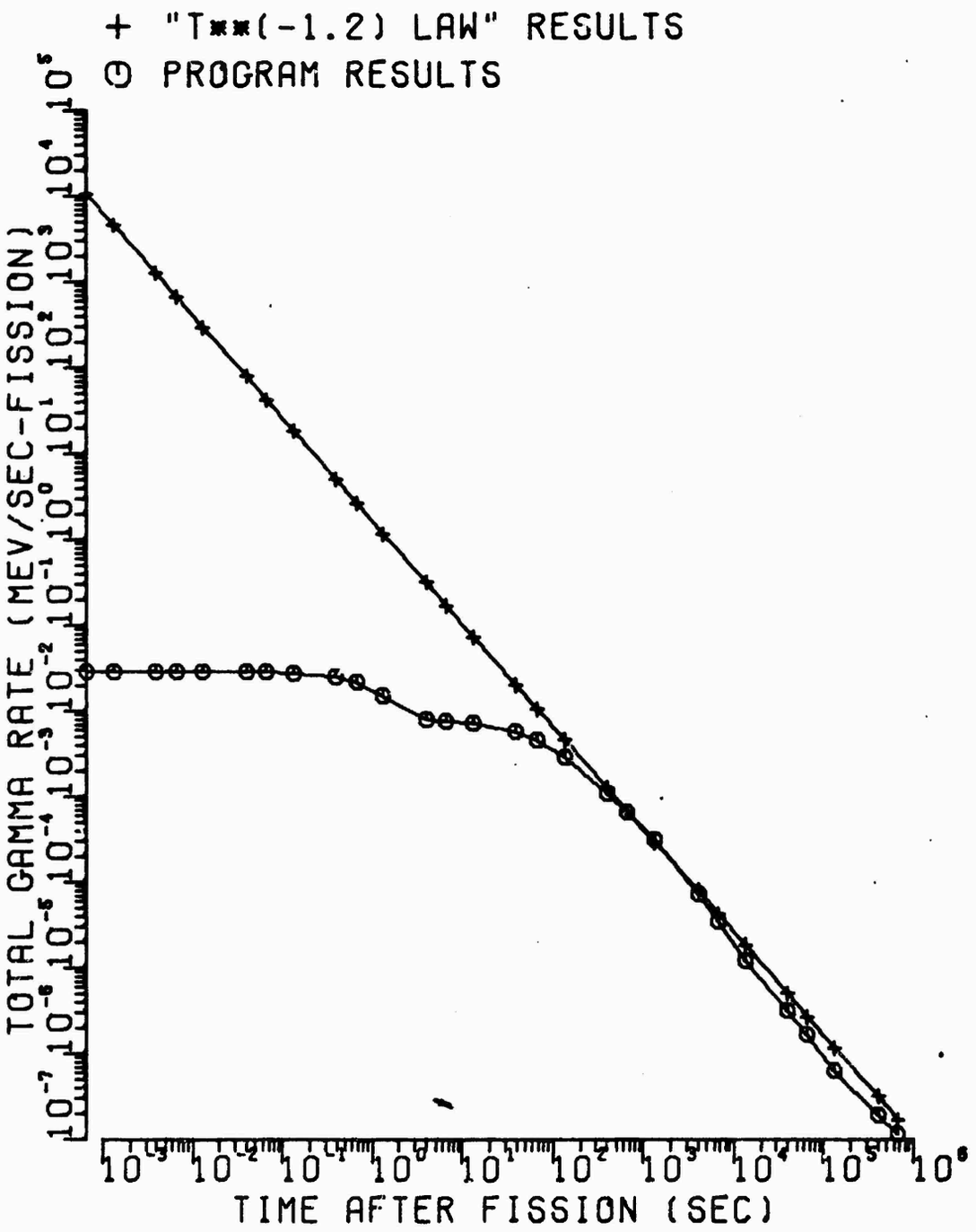


Figure 4. "$T^{-1.2}$ Law" Approximation Compared with Program Results.

gamma rate curves show "flattening" tendencies at times less than 1 to 100 sec after fission (Ref 11:1328, 2:2-19, 3:B811, 5:B822).

Independent Approximation

The various program result rates were analyzed in an attempt to find trends that could extend the long time total gamma energy rates into the short time region. The program total gamma energy rates and total activity rates were used to compute average gamma energy per decay values. A straight line approximation fits the average gamma energy per decay calues very well at times of 1000 sec to 10,000 sec after fission as shown in Figure 5. This time regime was selected because 1000 sec is the minimum time at which the program total energy rate results are considered valid. The straight line approximation for average gamma energy per decay is given by the following equation:

$$R(t) = R_o t^{-.104} \tag{12}$$

where: R_o is the average gamma energy per decay at unit time after fission.

t is the time after fission of interest in units compatible with R_o.

R(t) is the approximation of average gamma energy per decay for time t.

Figure 5 shows the program average gamma energy per decay values and approximation values based on the program value of 1.44 MeV/decay at 1000 sec. As would be expected, the approximated values are larger than program values as time goes below 1000 sec since program total gamma energy

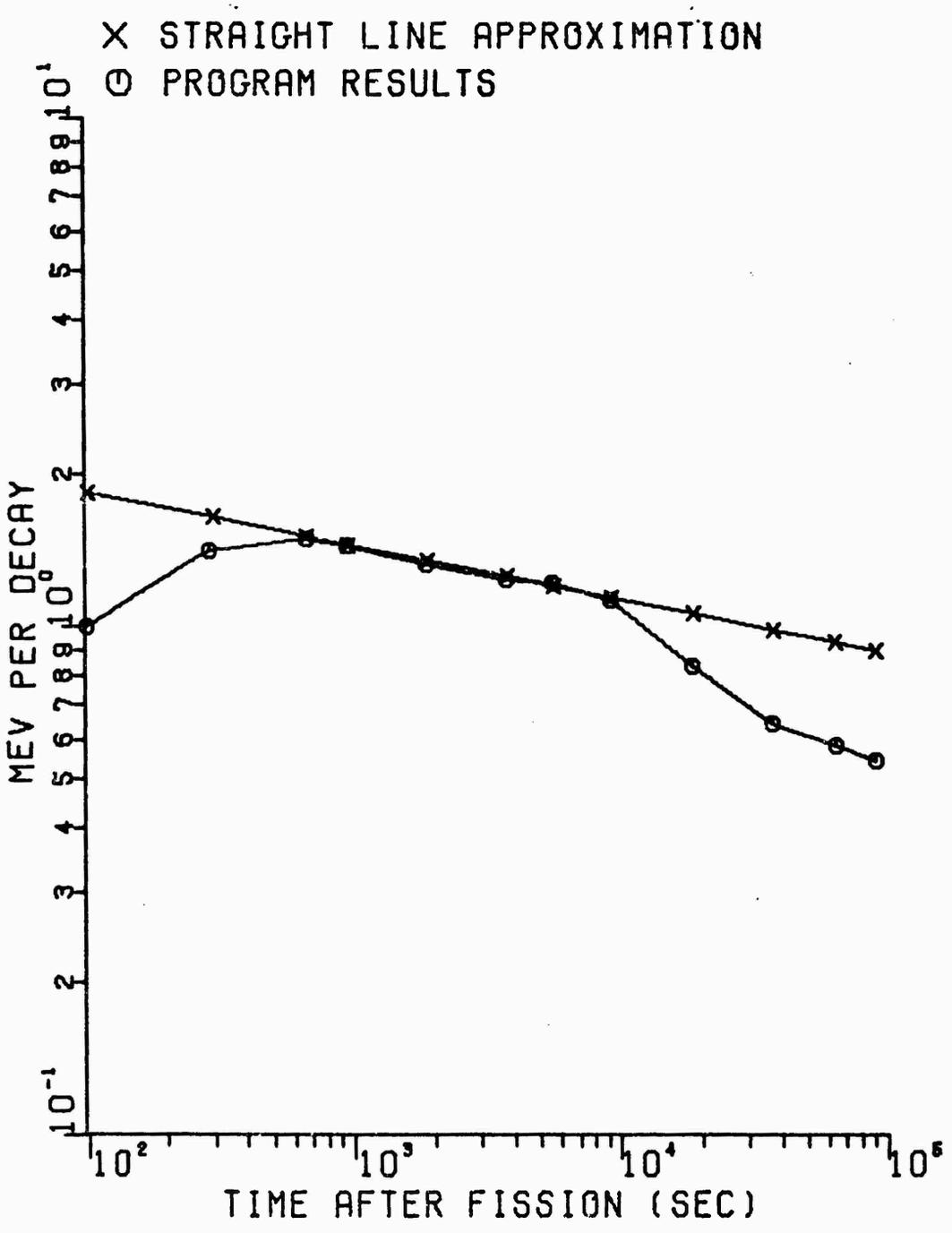


Figure 5. Average Energy per Decay - Program Results Compared with Straight Line Approximation

rates do not include gamma energy from some short lived product decays. As previously stated, program total activity rates are considered good for times down to 1 sec.

The approximated average gamma energy per decay values (MeV/decay) were then multiplied by program total activity rate values (decays/sec) to produce approximated total gamma energy rate values (MeV/sec) for times under 1000 sec. These results are compared to program results in Figure 6.

It should be noted that at times below 1 sec, the times when program total activity values are considered low, the approximated average gamma energy per decay values are increasing above 2.5 MeV/decay. Although actual cases where more than 2.5 MeV of gamma energy is released in a decay can be cited, such decays are rare. Thus while average gamma energy per decay values are probably high, for times less than 1 sec, and the total activity rate is considered low, these errors will tend to compensate each other, to some extent.

In Figure 7, some experimental values for total gamma energy rates from U^{235} as measured by Fisher and Engle in 1964 (Ref 2:B811) are compared with the independent approximation results. It should be noted that the 5 experimental values fall within, and pretty much cover, the .1 sec to 2 min after fission period of interest in this study. The experimental values fit the approximation results very well.

Integration of the approximation results over the time period 10^{-6} through 10^{12} sec results in a total gamma energy

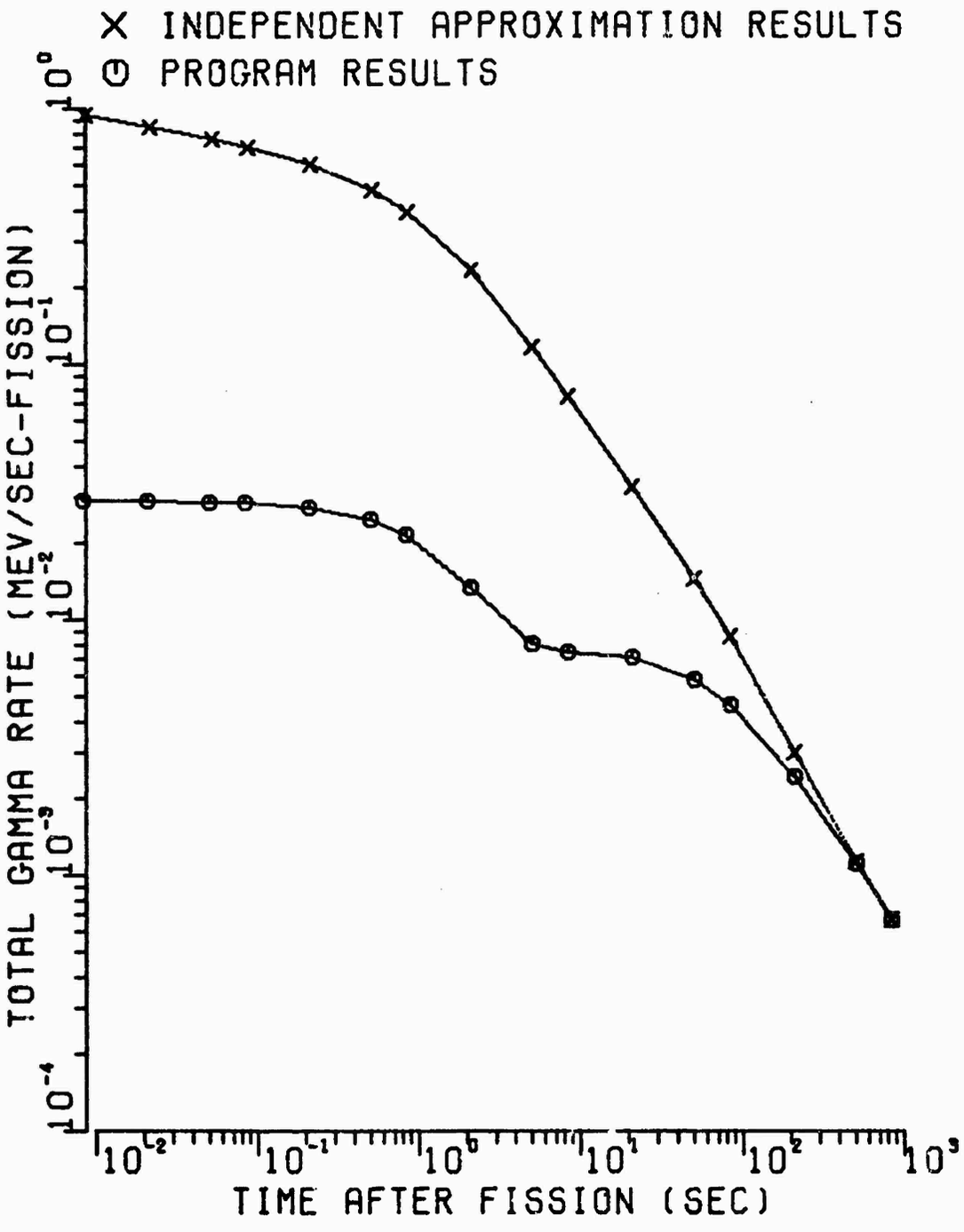


Figure 6. Total Gamma Energy Rate per Fission-Program Results Compared with Independent Approximation

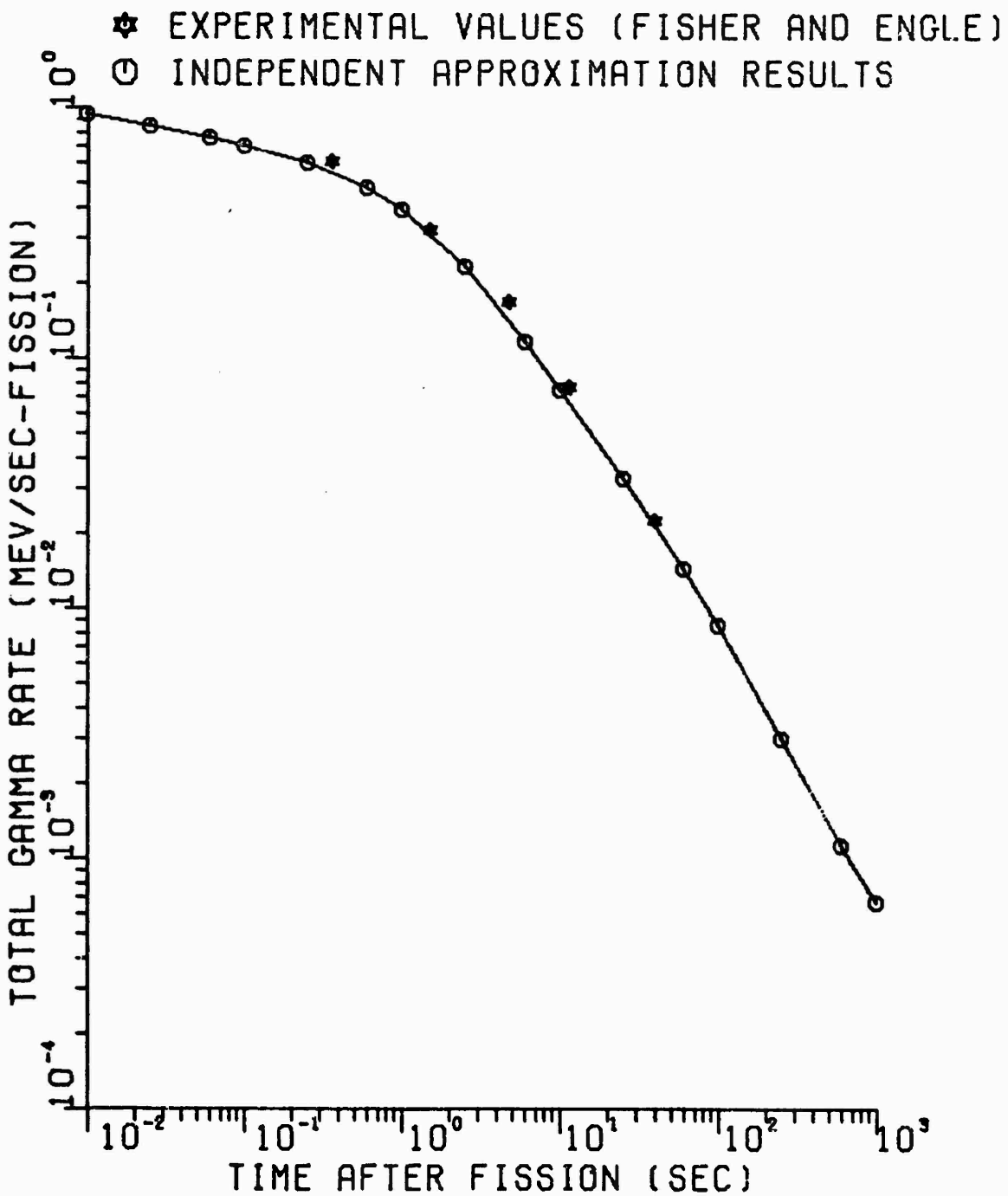


Figure 7. Total Gamma Energy Rate per Fission - Independent Approximation Compared with Experimental Values.

per fission value of 8.75 MeV/fission. This is close to the generally accepted value of 6 ± 1 MeV per fission (Ref 4:13).

Independent Approximation Compared with "Firefly" Approximation

The Air Force Weapons Lab, Kirtland AFB, N. M., is developing a code, "Firefly", to calculate weapon product radiation dose to aircraft. A memo (Ref 12) was supplied to the author describing the product gamma dose calculations proposed for use in the code.

The AFWL approximation uses a modification of the following equation (Ref 2:2-6) as a source of energy rate values.

$$A(t) = c(1 + t)^{-1.2} \qquad (13)$$

where: C = 1.9

t is the time after fission in seconds.,

A(t) is the total gamma energy rate (MeV/sec-fission) at time t.

This equation yields a total gamma energy per fission value of 9.5 MeV when integrated over the period t = 0 to ∞. For use in the Firefly code, equation 13 was scaled so that its integral would equal 7.7 MeV, the arithmetic mean of 9.5 MeV and the generally accepted value of 6.0 MeV (Ref 4:13). Thus equation 3, with C equal to 1.55, was used to compute total gamma energy rate values for the Firefly code. A comparison of the results of Firefly total gamma energy rate values with the author's independent approximation results is shown in Figure 8.

To evaluate the effects these two approximations would

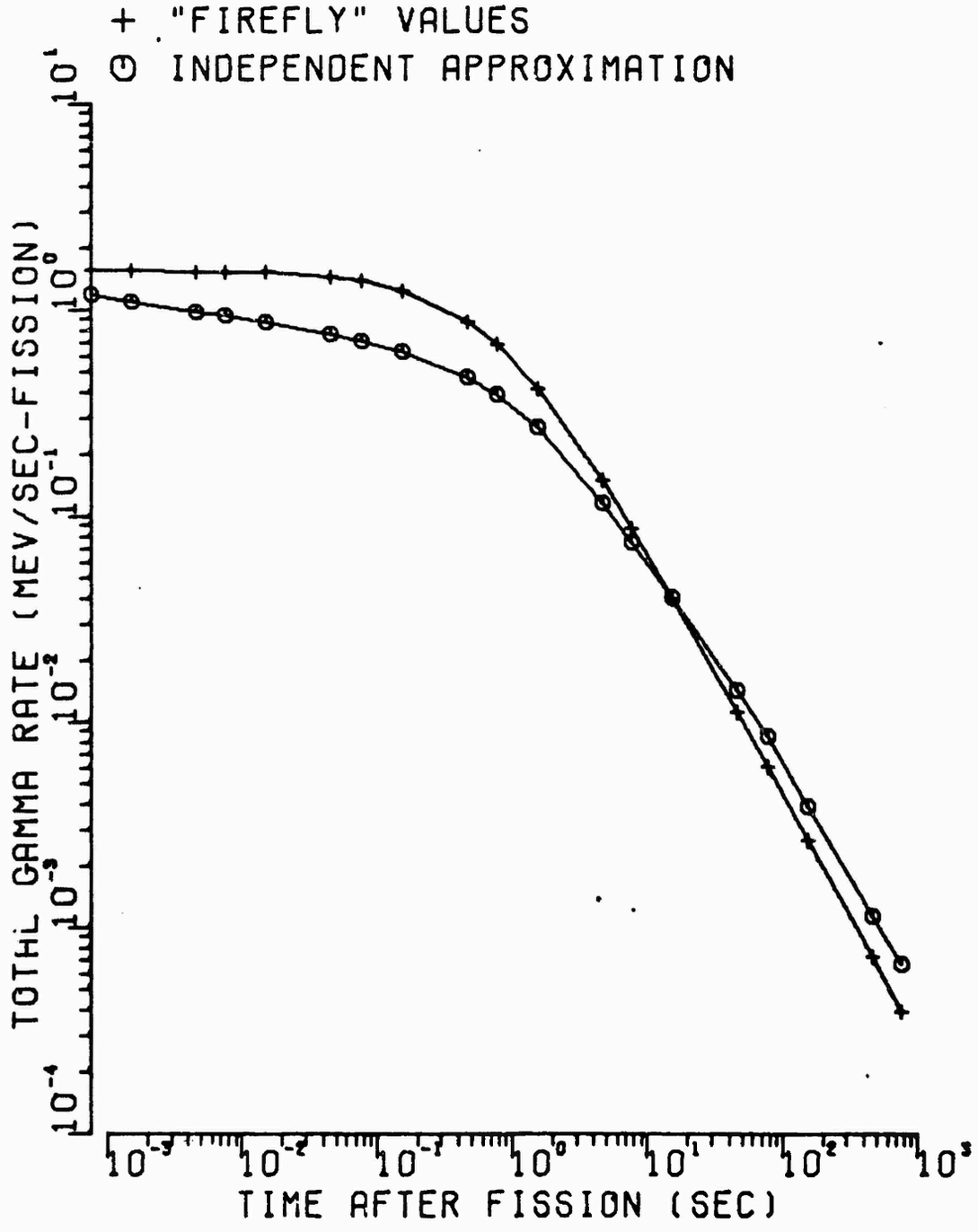


Figure 8. Total Gamma Energy Rate per Fission - Independent Approximation Compared with "Firefly" Approximation.

have on dose calculations, both were integrated over increasing time periods. Accumulated total gamma energy vs. time was plotted for both methods (see Figure 9). The independent approximation integration values differ by as much as 29% at 20 sec from the "Firefly" integration values.

The Firefly calculations use a fixed gamma spectrum based on the following equation (Ref 12:1):

$$\frac{dN(E)}{dE} = 1.1\ e^{-1.1E} \qquad (14)$$

where: N(E) is the number of gammas with energy E.

E is the gamma energy in MeV.

Although Firefly calculations used different gamma energy groups than this study, integration of equation 14 over appropriate energy ranges easily illustrates the Firefly spectrum in terms of the 17 energy groups used in this study (see Table I). Figure 10 compares the Firefly fixed spectrum with the spectrum calculated in this study at 1000 sec after fission. The gamma number values used are scaled so that total number of gammas over all groups equals .978, the integral of equation 4 over the energy range .02 to 8.0 MeV (the range of energy values covered in the 17 groups used in this study). It should be noted that the average gamma energy over this range of energies is .848 MeV for the "Firefly" spectrum and 1.054 MeV for the results of this study at 1000 sec after fission.

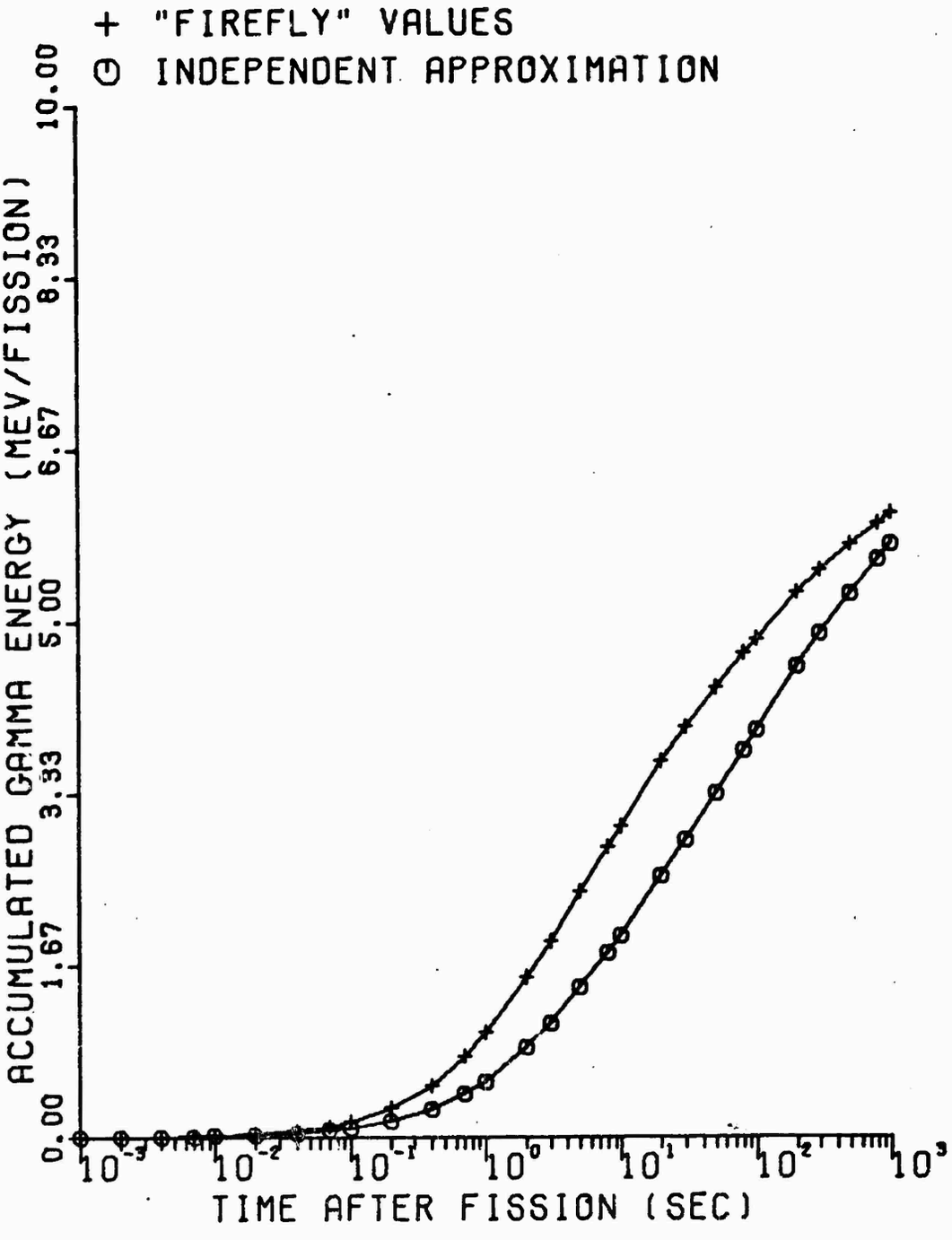


Figure 9. Accumulated Gamma Energy per Fission - Independent Approximation Compared with "Firefly" Approximation.

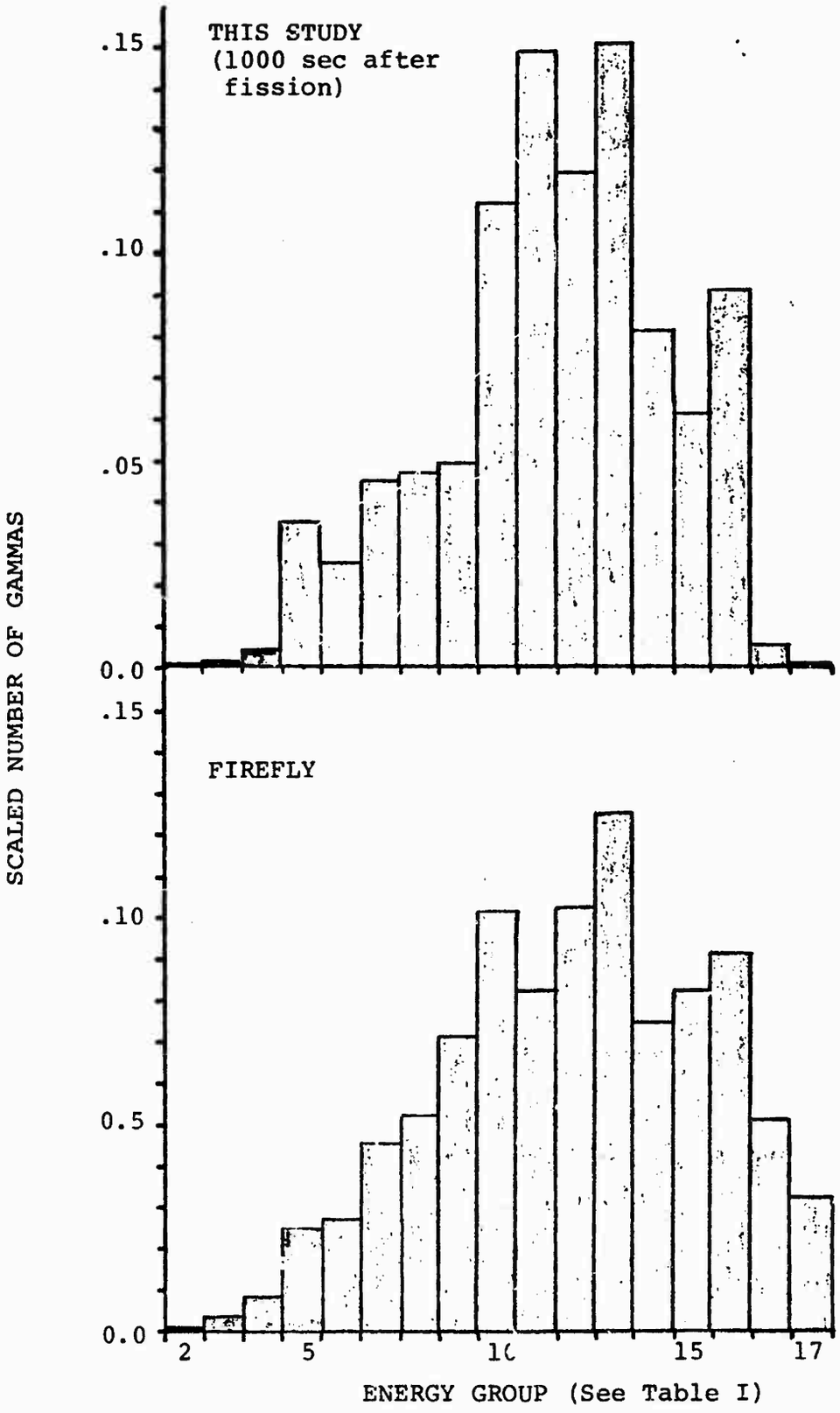


Figure 10. "Firefly" Spectrum Comparison.

V. Conclusions

For a device using only U^{235} (fission spectra) as a fuel, some of the results of this study can be used with confidence. Total activity values can be used for times after fission greater than 1 sec. Gamma group energy rates can be used for times greater than 1000 sec after fission. The program results can be used for total gamma energy rates for times down to 1000 sec after fission. The independent approximation results can be used for total gamma energy rates at times less than 1000 sec after fission.

Although, as previously mentioned, the results for devices composed of fuels other than U^{235} (fission spectra) were generally the same, it is felt the lower fraction of products included in the program for these fuels (see Table III) makes their results subject to more question than for the case of U^{235}. The results for other fuels might be slightly different if the missing fission products were accounted for in the program data.

If complete data could be obtained for the short lived fission products and added to the program data, the program could produce very accurate results for short times after fission. The calculation methods used in this study are simple and analytical. The results produced by this method are only limited by the accuracy and completeness of the fission yield and decay data used in the calculations.

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Appendix A

Computer Program

The computer program used in this study was written in FORTRAN IV language for use on the AFIT CDC-6600 computer. The main program (GAMA) and the subroutine (BATMN) listings are included in this report. The two data files containing fission yield and decay data are not included. They are considered too lengthy and to be of little interest to the majority of those who will read this report. A copy of the entire code is on file at the Physics Department (AFIT-ENP), Wright-Patterson AFB, Ohio.

```
****************** PROGRAM GAMA     PAGE 1 ****************

C*************************************************************
C*                                                           *
C*  PROGRAM GAMMA COMPUTES AND PRINTS OUT VARIOUS ENERGY     *
C*  AND NUMBER RATES AS DESCRIBED IN TABLE I FOR A FISSION   *
C*  DEVICE OF SPECIFIED YIELD AND COMPOSITION.  THE PROGRAM  *
C*  IS DIMENSIONED SO THAT OUTPUT FOR UP TO 50 TIMES AFTER   *
C*  FISSION WILL BE PRODUCED.                                *
C*                                                           *
C*  TAPE 5 MUST BE ATTACHED.  THIS FILE IS COMPOSED OF       *
C*  DECAY DATA (NC, N, NP, NFC, NBO, FF, GG, AND DC) FOR     *
C*  FISSION FRAGMENTS.  THE FILE USED FOR THIS STUDY         *
C*  INCLUDED DATA FOR 123 FISSION FRAGMENTS.  ALL FISSION    *
C*  FRAGMENTS ARE INDEXED AND FISSION FRAGMENT DECAY DATA    *
C*  MUST BE ARRANGED IN NUMERICAL ORDER ACCORDING TO THE     *
C*  INDEX NUMBERS.                                           *
C*                                                           *
C*  PROGRAM CONTROL PARAMETERS (NTIME,TA,YIELD, AND YCOMP)   *
C*  ARE ATTACHED AS A DATA DECK AND READ IN FROM THE FILE    *
C*  "INPUT".                                                 *
C*                                                           *
C*  SUBROUTINE BLOCK DATA MUST BE ATTACHED.  IT SETS VALUES  *
C*  FOR (YFF, NID, AND FPKT).                                *
C*                                                           *
C*  SUBROUTINE BATMN MUST BE ATTACHED.  IT CALCULATES THE    *
C*  RATE CONTRIBUTIONS OF EACH FISSION FRAGMENT AS           *
C*  DESCRIBED IN CHAPTER II.                                 *
C*                                                           *
C*  PROGRAM EXECUTION REQUIRES 37K AND 120 SEC TO COMPUTE    *
C*  OUTPUT RATES FOR 20 TIMES AFTER FISSION.                 *
C*                                                           *
C*************************************************************

      PROGRAM GAMA(INPUT,OUTPUT,TAPE5,PLOT)

      DOUBLE PRECISION GGTT(20,50),GGT(20)
      DIMENSION TA(52),YCOMP(7),FPKT(7),YFF(123,7),FF0(123),
     2NID(123),GGTP(52),N(3),NP(3),NFC(3),NBO(3),NBP(3,3),
     3BF(3,3),DC(10,3),GG(20,3,3)
      COMMON FF01,T,NC,N,NP,NFC,NBO,NBP,BF,DC,GG,GGT
      COMMON/FFD/YFF,NID,FPKT
```

```
 10   FORMAT (I5)
 11   FORMAT (8E10.3)
 20   FORMAT (8E10.4)
 70   FORMAT (*1*,*TOTAL GAMMA RATE*)
 71   FORMAT (*-*,*TIME AFTER BLAST*,5X,*GAMMAS PER SEC*,
     213X,*MEV PER SEC*,16X,*ACTIVITY (DECAYS PER SEC)*)
 72   FORMAT (* *)
 74   FORMAT (1X,1PE14.7,7X,1PD23.15,5X,1PD23.15,5X,1PD23.15)
 80   FORMAT (*-*,53(*-*),*FISSION FRAGMENT YIELDS*,53(*-*))
 81   FORMAT (*-*,*TOTAL NUMBER OF FISSIONS  *,1PE14.7,5X,
     2*RATIO= *,1PE14.7)
 82   FORMAT (*-*,*FF ID*,10X,*YIELD OF FF (NUMBER)*,5X,
     2*YIELD OF FF (FRACTION OF TOTAL FISSIONS)*)
 83   FORMAT (* *)
 85   FORMAT (1X,I4,*-*,I6,*G*,5X,1PE14.7,11X,F13.8)
 87   FORMAT (1X,I4,*-*,I6,*M*,5X,1PE14.7,11X,F13.8)
 90   FORMAT (*1*,57(*-*),*WEAPON DATA*,57(*-*))
 91   FORMAT (*-*,*TOTAL YIELD  *,1PE10.3,*  KILO TONS*)
 92   FORMAT (*-*,*FUEL FRACTIONS*)
 93   FORMAT (*-*,*U235(FS)*,7X,*U238(FS)*,7X,*PU239(FS)*,
     26X,*U235(14MEV)*,4X,*U238(14MEV)*,4X,*PU239(14MEV)*,
     34X,*  OTHER*,8X)
 94   FORMAT (1X,7(1PE10.3,5X))
150   FORMAT (8I10)
151   FORMAT (8F10.7)
152   FORMAT (4D20.13)
200   FORMAT (*1GROUP GAMMA RATES*)
201   FORMAT (*-TIME AFTER BLAST*,3X,*        *,12X,*GROUP 2*,
     212X,*GROUP 3*,12X,*GROUP 4*,12X,*GROUP 5*,12X,*GROUP 6*)
203   FORMAT (1X,1PE14.7,24X,5(1PD14.7,5X))
204   FORMAT (*-TIME AFTER BLAST*,3X,*GROUP 7*,12X,*GROUP 8*,
     212X,*GROUP 9*,12X,*GROUP 10*,11X,*GROUP 11*,11X,
     3*GROUP 12*)
206   FORMAT (*-TIME AFTER BLAST*,3X,*GROUP 13*,11X,
     2*GROUP 14*,11X,*GROUP 15*,11X,*GROUP 16*,11X,
     3*GROUP 17*,11X,*GROUP 18*)
208   FORMAT (1X,1PE14.7,5X,6(1PD14.7,5X))


C*****************************************************************
C*                                                               *
C*  READ IN PROGRAM CONTROL PARAMETERS.                          *
C*                                                               *
C*****************************************************************

      READ 10,NTIME
      READ 11,(TA(I),I=1,NTIME)
      READ 20,YIELD,(YCOMP(I),I=1,7)
```

```
C*****************************************************************
C*                                                               *
C*  COMPUTE THE YIELD (NUMBER OF ATOMS) OF EACH FISSION          *
C*  FRAGMENT PRODUCED.                                           *
C*                                                               *
C*****************************************************************

      DO 25 J=1,123
      FF0(J)=0.
      DO 25 I=1,7
 25   FF0(J)=FF0(J)+YFF(J,I)*YCOMP(I)*YIELD*FPKT(I)


C*****************************************************************
C*                                                               *
C*  COMPUTE THE RATIO OF THE ACTUAL TOTAL NUMBER OF FISSION      *
C*  FRAGMENTS (2 TIMES THE TOTAL NUMBER OF FISSIONS) TO THE      *
C*  COMPUTED TOTAL NUMBER OF FISSION FRAGMENTS.                  *
C*                                                               *
C*****************************************************************

      FF0TOT=0.
      DO 30 J=1,123
 30   FF0TOT=FF0TOT+FF0(J)
      FTOT=0.
      DO 35 J=1,7
 35   FTOT=FTOT+YIELD*YCOMP(J)*FPKT(J)
      PATIO=(2.*FTOT)/FF0TOT


C*****************************************************************
C*                                                               *
C*  PRINT OUT PARAMETERS DESCRIBING THE DEVICE.                  *
C*                                                               *
C*****************************************************************

      PRINT 90
      PRINT 91,YIELD
      PRINT 92
      PRINT 93
      PRINT 94,YCOMP(1),YCOMP(2),YCOMP(3),YCOMP(4),YCOMP(5),
     2YCOMP(6),YCOMP(7)
 50   PRINT 81,FTOT,PATIO
```

```
C*****************************************************************
C*                                                               *
C*  A LIST INCLUDING EACH FISSION FRAGMENT INDEX NUMBER,         *
C*  FISSION FRAGMENT IDENTIFICATION (ATOMIC NUMBER, MASS         *
C*  NUMBER, AND STATE), DEVICE YIELD OF THAT FRAGMENT            *
C*  (NUMBER OF ATOMS) AND FRACTIONAL YIELD IS PRINTED OUT.       *
C*                                                               *
C*****************************************************************

      PRINT 80
      PRINT 82
      PRINT 83
      DO 84 I=1,123
      PC=(FF0(I)/FTOT)*.1
      IF (I .EQ. 33) GO TO 86
      IF (I .EQ. 37) GO TO 86
      IF (I .EQ. 40) GO TO 86
      IF (I .EQ. 46) GO TO 86
      IF (I .EQ. 53) GO TO 86
      IF (I .EQ. 57) GO TO 86
      IF (I .EQ. 90) GO TO 86
      IF (I .EQ. 95) GO TO 86
      IF (I .EQ. 109) GO TO 86
      IF (I .EQ. 112) GO TO 86
      IF (I .EQ. 115) GO TO 86
      PRINT 85,I,NID(I),FF0(I),PC
      GO TO 84
 86   PRINT 87,I,NID(I),FF0(I),PC
 84   CONTINUE


C*****************************************************************
C*                                                               *
C*  READ FISSION FRAGMENT DECAY PARAMETERS FOR A FISSION         *
C*  FRAGMENT, COMPUTE RATE CONTRIBUTIONS OF THE FRAGMENT         *
C*  AND ADD THEM TO RUNNING TOTALS.  REPEAT FOR EACH             *
C*  FISSION FRAGMENT.  REPEAT THE PROCESS FOR EACH TIME          *
C*  AFTER FISSION.  NOTE---ALL INITIAL FISSION FRAGMENT          *
C*  NUMBERS ARE MULTIPLIED BY RATIO SC AN ADJUSTED 100%          *
C*  FISSION YIELD COVERAGE WILL BE REFLECTED IN THE OUTPUT.      *
C*                                                               *
C*****************************************************************
```

```
      DO 65 K=1,NTIME
      T=TA(K)
      DO 55 J=1,20
 55   GGT(J)=0.
      DO 160 KK=1,130
      FF01=FF0(KK)*RATIO
      READ (5,150) NC,(N(I),I=1,3),(NB(I),I=1,3)
      IF (EOF(5) .NE. 0) GO TO 170
      READ (5,150) (NBC(I),I=1,3),(NBO(I),I=1,3)
      DO 140 J=1,NC
 140  READ (5,150) (NBP(I,J),I=1,3)
      DO 141 J=1,NC
 141  READ (5,151) (BF(I,J),I=1,3)
      DO 142 J=1,NC
      NN=N(J)
      DO 142 JJ=1,NN
 142  READ (5,151) (GG(I,JJ,J),I=1,20)
      DO 143 J=1,NC
      NN=N(J)
 143  READ (5,152) (DC(I,J),I=1,NN)
      CALL BATMN
 160  CONTINUE
 170  REWIND 5
      DO 64 J=1,20
 64   GGTT(J,K)=GGT(J)
 65   CONTINUE


C*****************************************************************
C*                                                               *
C*  PRINT THE COMPUTED RATES FOR EACH TIME AFTER FISSION.        *
C*                                                               *
C*****************************************************************

      PRINT 70
      PRINT 71
      PRINT 72
      DO 73 I=1,NTIME
 73   PRINT 74,TA(I),GGTT (19,I),GGTT(20,I),GGTT(1,I)
      PRINT 200
      PRINT 201
```

```
      PRINT 72
      DO 202 I=1,NTIME
 202  PRINT 203,TA(I),(GGTT(J,I),J=2,6)
      PRINT 200
      PRINT 204
      PRINT 72
      DO 205 I=1,NTIME
 205  PRINT 208,TA(I),(GGTT(J,I),J=7,12)
      PRINT 200
      PRINT 206
      PRINT 72
      DO 207 I=1,NTIME
 207  PRINT 208,TA(I),(GGTT(J,I),J=13,18)
      STOP
      END
```

Program GAMA Variable Definitions:

NTIME	- The number of times after fission for which results are desired.
TA(I)	- The times after fission in sec.
Yield	- Total fission yield of the device in kilo-tons TNT.
YCOMP(I)	- The fraction of the total yield from the Ith fuel. Table II lists the fuels in order, eg fission spectra U^{235} is fuel 1.
YFF(I,J)	- The fission yield of fragment I for the fission of fuel J.
NID(I)	- The identification (atomic number and weight) of fission fragment I.
FPKT(J)	- The number of fissions of fuel J needed for one kilo-ton of yield.
GGTT(I,J)	- The output, ie the rate I for time J after fission.

```
C*****************************************************************
C*                                                               *
C*  SUBROUTINE BATMN COMPUTES THE RATE CONTRIBUTIONS OF A        *
C*  FISSION FRAGMENT AND ADDS THEM TO RUNNING TOTALS FOR         *
C*  THE TIME AFTER FISSION BEING PROCESSED.                      *
C*                                                               *
C*  THE INTIAL NUMBER OF ATOMS OF THE FRAGMENT, THE TIME         *
C*  AFTER FISSION, AND FRAGMENT DECAY PARAMETERS ARE THE         *
C*  INPUTS TO SUBROUTINE BATMN.                                  *
C*                                                               *
C*****************************************************************

      SUBROUTINE BATMN

      DOUBLE PRECISION GGT(20),GGS(20),GGSS(20)
      DIMENSION N(3),NB(3),NPC(3),DC(10,3),GG(20,10,3),
     2NBO(3),NBP(3,3),BF(3,3),EX(10),C(10)
      COMMON  FFO,T,NC,N,NB,NPC,NBO,NBP,BF,DC,GG,GGT

      DO 1 I=1,20
1     GGS(I)=0.


C*****************************************************************
C*                                                               *
C*  THE INPUTS ARE USED TO SET UP DECAY EQUATIONS (AS            *
C*  ILLUSTRATED BY EQUATIONS  7-10) FOR THE PARTICULAR           *
C*  FRAGMENT AND ITS DAUGHTERS.  THE CALCULATIONS ARE THEN       *
C*  MADE AS DESCRIBED IN CHAPTER II TO COMPUTE THE RATE          *
C*  CONTRIBUTIONS FOR THIS FRAGMENT.                             *
C*                                                               *
C*****************************************************************

      DO 200 II=1,NC
      N1=N(II)
      N2=NB(II)
      N3=NBO(II)
      DO 4 I=1,N1
4     EX(I)=EXP(-DC(I,II)*T)
      DO 3 I=1,20
```

```
3       GGSS(I)=0.
        DO 8 K=N2,N1
        DO 9 I=1,K
        C(I)=DC(K,II)*FF0
        DO 17 M=1,N3
        N4=NBP(M,II)
        IF (K .GT. N4) C(I)=C(I)*BF(M,II)
        IF (K .EQ. N4) C(I)=C(I)*BF(M,II)
 17     CONTINUE
        IF (K .EQ. 1) GO TO 9
        DO 5 J=1,K
        IF (J .EQ. K) GO TO 25
        IF (J .EQ. I) GO TO 20
        C(I)=C(I)*DC(J,II)/(DC(J,II)-DC(I,II))
        GO TO 5
20      C(I)=C(I)*DC(J,II)
        GO TO 5
25      IF (I .EQ. K) GO TO 5
        C(I)=C(I)/(DC(J,II)-DC(I,II))
    5   CONTINUE
9       CONTINUE
        A=0.
        DO 6 J=1,K
 6      A=A+C(J)*EX(J)
        DO 7 J=1,20
7       GGSS(J)=GGSS(J)+GG(J,K,II)*A
8       CONTINUE
        DO 121 I=1,20
121     GGS(I)=GGS(I)+GGSS(I)
200     CONTINUE


C*****************************************************************
C*                                                               *
C*  THE FRAGMENT RATE CONTRIBUTIONS ARE ADDED TO RUNNING         *
C*  TOTALS FOR THE TIME AFTER FISSION BEING PROCESSED.           *
C*                                                               *
C*****************************************************************

        DO 122 I=1,20
122     GGT(I)=GGT(I)+GGS(I)
        RETURN
        END
```

Subroutine BATMN Variable Definitions:

FFO	- The initial number of atoms of the fission fragment created by the device.
T	- The specified time after fission (sec).
GGT(I)	- A running total of rate I: eg GGT(I) is the total activity rate (decays/sec).
GGS(I),GGSS(I)	- Internal subroutine summations of rate I.
NC	- The number of chains in the decay of this fission fragment (See Appendix A).
N(I)	- The number of radioactive members along the Ith chain.
NB(I)	- The first member of chain I that branches.
NPC(I)	- The chain that chain I branches off of.
NBO(I)	- The number of branching members along chain I.
NBP(J,I)	- The Jth member of chain I that branches.
BF(J,I)	- The branching fraction of the Jth member of chain I that branches.
DC(J,I)	- The decay constant of the Jth member of chain I (sec^{-1}).
GG(K,J,I)	- The Kth decay factor of the Jth member of chain I: eg GG (20, 3, 2) would be the total gamma energy produced by one decay of the 3rd member of the 2nd chain.

Vita

Ronald B. Drinkwater was born on [redacted] PII Redacted [redacted]. He graduated from [redacted] in 1960, and attended the USAF Academy, receiving his Bachelor of Science degree upon graduation in 1964. He received a commission in the US Air Force in 1964, attended pilot training, and spent 8 years in various flying assignments. In 1972 he entered the Air Force Institute of Technology where he received a Master of Science degree in Nuclear Engineering.

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This thesis was typed by [redacted] PII Redacted